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Monterey, California

THESIS

H58265

FLOW VISUALIZATION ON A SMALL SCALE

by

Roy L. Hixson III

March 1988

Thesis Advisor: J. Val Healey

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Flow Visualization on a Small Scale

by

Roy Lester Hixson III
Commander, United States Navy
B.S., Oregon State University, 1973
M.B.A., Chapman College, 1982

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
March 1988

ABSTRACT

A quarter scale model of the planned renovated form of an existing flow visualization tunnel was designed and constructed to test the quality of flow and for small scale research and flow visualization demonstrations. Three flow visualization techniques were developed, including fog injection, helium bubbles, and smoke wire. In addition to velocity calibration and test section mapping of the tunnel, the latter two of these methods were used for visualizing flows around three different shaped bodies as demonstration that the tunnel's design objectives were realized. Both techniques produced excellent photographic results of flows around a block of rectangular cross section, a circular cylinder and an airfoil.

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I. INTRODUCTION

A. PURPOSE OF FLOW VISUALIZATION

To increase knowledge and insight into the workings and effects of many physical processes, visual observation is often the most enlightening. In fluid flow problems, understanding of the physics of the flow is greatly enhanced through visual surveillance. By observing the flow patterns of a fluid around an obstacle, which may be stationary or variable with time, it is possible to obtain an idea of the complete development of the flow.

Because most liquids are transparent, they are invisible to the human eye. Techniques must be developed, therefore, to make the flow visible. These techniques as a whole are called flow visualization and have continued to play an important role in understanding and solving fluid mechanics problems.

In addition to basic understanding of flow phenomenon, quantitative data may also be derived from the flow picture and is of much greater importance. These techniques provide information about the flow field with minimum interference of the fluid. This is in contrast to a single flow measuring device, such as a hot wire or pitot probe, which provides single point data and always disturbs the flow to some degree. This disturbance can significantly affect the experimental results in certain types of flow phenomenon. [Ref. 1:p. 1]

B. GENERAL METHODS OF FLOW VISUALIZATION

As discussed by Merzkirch [Ref. 1:pp. 2-3], methods of flow visualization can be classified into three basic categories.

1. Visible Material Addition to the Flow

First, and most common, are techniques in which a foreign material is added to the flowing fluid. The material must be visible and small enough so that it follows the motion of the fluid in direction and magnitude. Actually, the motion of the material is viewed instead of the fluid itself, and is thus an indirect observation. These methods are quite accurate for stationary flows but can have large errors for unsteady flows. Care must also be taken to ensure that the density and temperature of the material are as close to that of the fluid as possible to avoid errors. This is especially true in compressible flows.

2. Optical Methods

A second family of techniques was developed to avoid the problems associated with the first technique in compressible flows. Because the refractive index of a fluid is a function of the fluid density, compressible flows can be made visible by use of optical methods that are sensitive to this change in the index of refraction.

A standard set-up would have a light beam transmitted through the flow field in which the beams' optical phase is altered with the change in density. An optical device behind the field provides recording through the uneven illumination caused by the phase change in the light beam as it passes through the compressible flow being studied.

Optical methods are purely nondisturbing. However, quantitative evaluation can be difficult because the recorded information is in fact an integration of the density change along the light path.

3. Energy Addition to the Flow

A third technique is a combination of the first two. In this case the foreign matter introduced into the flow is energy, usually in the form of heat or electricity. Fluid elements are thus marked by their increased energy level. The particles, at times, require separate illumination to observe this increase in energy, however, some methods provide enough energy increase that the particles can easily be observed.

This technique is most applicable to rarefied or low-density gas flows. To some degree, this technique does disturb the flow according to the amount of energy released.

C. TECHNIQUES INVOLVING MATERIAL ADDITION

Because current research at the Naval Postgraduate School (NPS) in Monterey, California is primarily centered around varieties of the first technique described above, further background will focus on these methods.

The use of smoke for flow visualization at low subsonic speeds is traced to Dr. Ludwig Mach in 1893. Machs' techniques included silk threads, cigarette smoke and glowing iron particles. During 1900-1901, E.J. Marey extended knowledge of liquid flows and produced excellent wood smoke photographs. Although many other small low speed wind tunnels followed these developments, Professor F.N.M. Brown at the University of Notre Dame was the first to develop a large three dimensional research smoke tunnel capable of speeds up to 67 meters per second in 1950. This tunnel was the successor to his work with two and three dimensional smoke tunnels which began in 1935. Brown is credited with most refinements to the various smoke visualization techniques and many of his practices and designs have been copied in subsequent years. [Ref 2:p. 87]

The generation of a thin jet of smoke into a stream of air is the most popular method of visualizing low turbulence flow patterns in air flow. By increasing the number of sources of the smoke and making them into a sheet, three dimensional flow studies may be performed.

Streamlines, streaklines and pathlines are three curves that help describe the flow of a fluid. A streamline is a curve everywhere parallel to the direction of flow (also defined as the curve everywhere tangent to the instantaneous velocity vectors). A streakline is the locus of all particles that have passed through a fixed point during a specified period of time. And, a pathline is the curve traversed by an individual particle during a specified period of time. In steady flows, these three curves are the same.

1. Smoke Wire

There are some fundamental flow phenomena that require the ability to produce small but discrete smoke filaments (streaklines) and to locate these filaments accurately within the flow field so that small-scale details may be studied. One method that is quite simple and allows easy control of the generation of the smoke sheet is through the use of a smoke wire. In this design, which was initially proposed in the early 1950s by numerous researchers, a metal wire is painted with a mineral or vegetable oil. The wire is placed perpendicularly to the air stream after which a strong instantaneous electric current is sent through the wire to produce a white colored smoke mist suitable for photography.

A series of photographs of the smoke movement illuminated by a strobe-light will reveal not only the movement but will yield the velocity distribution. Because the smoke mist is easily diffused into the flow, it should only be used for observation of stationary flows with relatively low speeds (less than 20 meters per second), and is ideally suited to applications where the Reynolds number based on wire diameter is small (~20.0). [Ref. 3:p. 9]

More complex three dimensional flow fields may be studied and photographed by use of the smoke wire rake. This technique simply uses a long wire (or individual wires with a common current source) with multiple bends arranged to create lengths of wire parallel to each other. This structure is held together by an insulator "rake" at the bends (or ends of the individual wires). This complete smoke wire rake is then placed perpendicularly to the stream.

It should be noted that the oil usually lasts for only one operation. Also, it takes a couple of milliseconds after applying the electric current until the mist is produced.

2. Injection

The smoke tube or smoke injection method usually does not provide the fine details of the flow obtainable with the smoke wire technique. In this method the smoke is produced by a smoke generator that is separate from and outside of the flow tunnel. The smoke is then transferred to the area of interest via tubes where it can be injected through a nozzle directly into the flow field at or upstream of the field of study. As with the smoke wire technique, multiple linear streams may be produced by use of a perpendicularly placed tube rake which will allow three dimensional analysis.

Often the rake is placed outside the tunnel directly in front of the intake throat which allows the smoke streams to be contracted with the rest of the intake air. The result is smaller diameter, steadier streams which are more suitable to fine detail photography. The placement of the rake outside the intake also permits the experimenter to easily and quickly move the smoke streams to desired locations within the flow field while the tunnel is in operation. When studying flows around specifically shaped objects, such as an airfoil, single or multiple point injection at particular points on the object allows careful and precise analysis of the stream lines from the injection points down-stream.

3. Neutrally Buoyant Bubbles

Injection of neutrally buoyant helium-filled bubbles (of about 1mm in diameter) into the air stream is a technique developed to alleviate some of the problems associated with diffusion of smoke mist or other methods using small airborne particles. As discussed by Goldstein [Ref. 4:pp. 341-342], the soap bubble is an ideal particle because its size and buoyancy can be controlled. The first use of soap bubbles for flow visualization in wind tunnels appears to be by Redon and Vinsonneau in 1936 at Marseille, France and through refinements evolved into the modern system begun by Hale, Tan, Stowell and Ordway in 1967. The complete system consists of a bubble generator, lighting and optical components for illuminating the bubbles. The bubble generator consists of a head in which the bubbles are actually formed and a console that supplies the constituents to the head. Neutral buoyancy is achieved by filling the bubbles with helium. The console meters the helium, a bubble film solution (BFS), and air to control bubble size, and weight.

The paths traced by the bubbles map streakline patterns of the injected film air mixing with the mainstream. Unlike fog or smoke which diffuses rapidly, the bubble streaklines are clearly identifiable as continuous thread-like streaks which can be traced through the film injected region, and accordingly, may be used for flows where turbulence is involved. [Ref. 5:p. 45]

II. CURRENT STATUS AT THE NAVAL POSTGRADUATE SCHOOL

A. DESCRIPTION OF PRESENT FACILITY

The current low speed/low turbulence wind tunnel at NPS is essentially a three dimensional smoke tunnel with helium bubble and aerosol (smoke mist) injection capability. Described by Bolinger [Ref. 6:pp. 16-18], the tunnel is modeled after the tunnel located at the Naval Engineering Laboratory in Philadelphia, Pennsylvania [Ref. 7]. It draws air through three inches of honeycomb and a screen into a 9 to 1 square bell contraction cone. The inlet area is 15 x 15 feet and contracts to a 5 x 5 foot square test section that is 22 feet long.

After flowing through the contraction cone and the test section, the air then passes through a set of louvers and transitions to a circular duct. Behind the louvers in the circular duct is the fan and motor used to drive the tunnel. The fan has variable pitch blades, which are used to control the tunnel velocity. Next, the exhaust air is turned 90 degrees upward, where it is vented to the outside atmosphere.

The roof and sides of the tunnel have a variety of plexiglass windows, ranging from 12 x 18 inches to over 4 x 4 feet, which are used for viewing, lighting, and photographing models in the test section. To improve the photographic contrast, the interior of the tunnel is painted with low reflective flat black paint.

B. NEED FOR A NEW TUNNEL

Existing plans at NPS call for renovation and relocation of the current tunnel to a site approximately two miles from the main campus. The renovation will include changing the current square shape of the test section to rectangular to improve resolution of measurements around ship models and the addition of a small contraction cone at the end of the test section. Thus, a quality check of the flow in this new configuration is needed before final construction begins.

With only one low speed/low turbulence flow visualization tunnel existing now and planned for the near future, researchers are limited to physical scales that match the size of the test section. Often, smaller scale research can produce equally informative results at a fraction of both the time and money, however, with only one tunnel this option is not currently available.

As discussed earlier, flow visualization is often the most dramatic and useful tool in understanding fluid flow mechanics. The aeronautical engineering curriculum and the majority of other technical curriculum at the NPS include fluid flow analysis in their core courses. The use of flow visualization should therefore be among the basic tools used in teaching this area of study. However, because of the current tunnel's location and somewhat cramped viewing station, it is unsuitable for class demonstrations where more than a few people are present. In addition, the current tunnel is in constant use for research and is therefore unavailable for demonstrations should the location and viewing station be updated. Besides, it is expected that it will be relocated soon.

Therefore, a second smaller tunnel that could be used for class demonstrations, and small scale basic research is highly desirable. Additionally, if the design were close to that of the renovated tunnel, quality-of-flow analysis could be performed.

The purpose of this investigation was twofold. The first portion of the study was to design and construct a small scale flow visualization tunnel within the design parameters listed in Chapter III. The second part was to incorporate three basic flow visualization techniques consisting of smoke injection, smoke wire and helium bubbles, and to demonstrate the latter two.

III. DESIGN PARAMETERS

A. PHYSICAL DIMENSIONS AND MATERIALS

The first concern was to ascertain the physical dimensions of the complete tunnel and the test section in particular. Initially, a decision was required on the material to be used and the cost of construction, which is directly related. Although commercial tunnels were available, their designs did not match closely enough the renovated tunnel which needed flow quality checks and, more importantly, they were very expensive. In trying to keep the costs at a minimum it was decided to use readily available materials (wood and plexiglas where appropriate) and any surplus assemblies, when available. Additionally, all design and construction would be performed in-house at NPS.

As a secondary mission, the tunnel will be used for demonstrating basic flow mechanics. Therefore, initial estimates called for a tunnel of overall size small enough to allow quick set up for class demonstrations. On the other hand, the device should be of sufficient size to allow viewing by a group of people, some of whom are not immediately close to the tunnel.

The most complex assembly is the fan housing and motor mount. Because a complete surplus drive unit of wood/steel construction was available, consisting of the fan assembly, 90 degree turning vanes, motor mount, and exhaust air duct intact, this was the starting point for initial design. Combining the dimensions of this housing with the requirements listed above, design results best suited a one quarter scale model of the renovated tunnel, which would fit on a nine foot table.

The resultant tunnel design, as shown in Figures 1 and 2, draws air through one inch of 1/4 inch cell honeycomb and two screens, the first 1/8 inch mesh and the second 1/16 inch mesh, into a 6.75 to 1, formed plexiglas, square bell contraction cone. The inlet of this cone has inside dimensions of 45 x 54 inches and contracts down to a 15 x 24 inch plexiglas test section that is 70.75 inches long. The top of this portion is attached with hinges on one side to accommodate easy access to the test section. Included at the end of the test section is a 17.75 inch long rectangular cone with a slight contraction of 1.6 to 1. This cone is designed after the cone to be installed on the refurbished tunnel and is included to insure realistic and similar quality of flow. The entire tunnel from the test section forward can be rotated 90 degrees should experimentation require.

After flowing through the contraction cone and the test section, the air then passes through a 14.25 inch long rectangular to octagonal shaped wood conversion section for

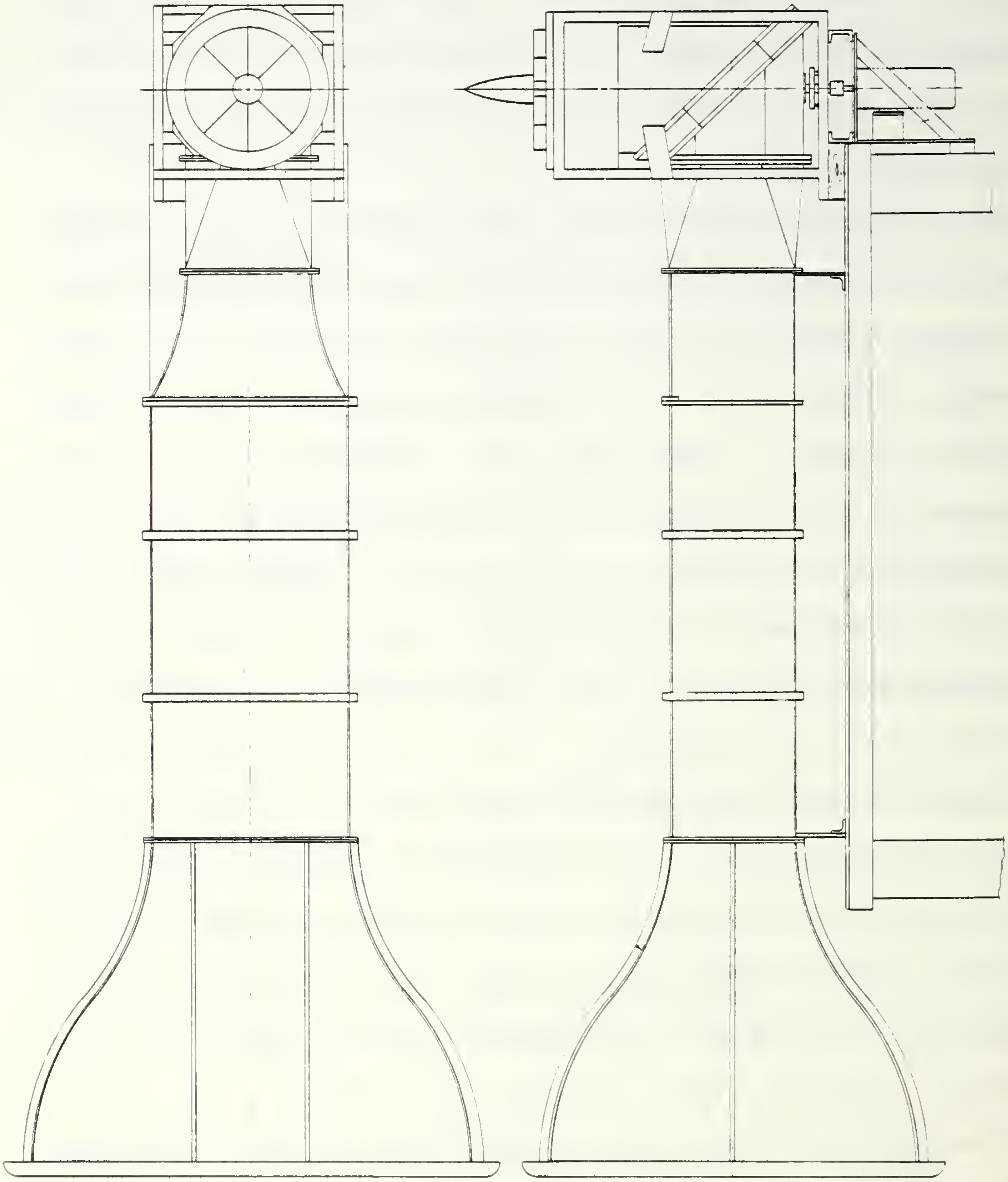

Figure 1. The Original Design for the Tunnel

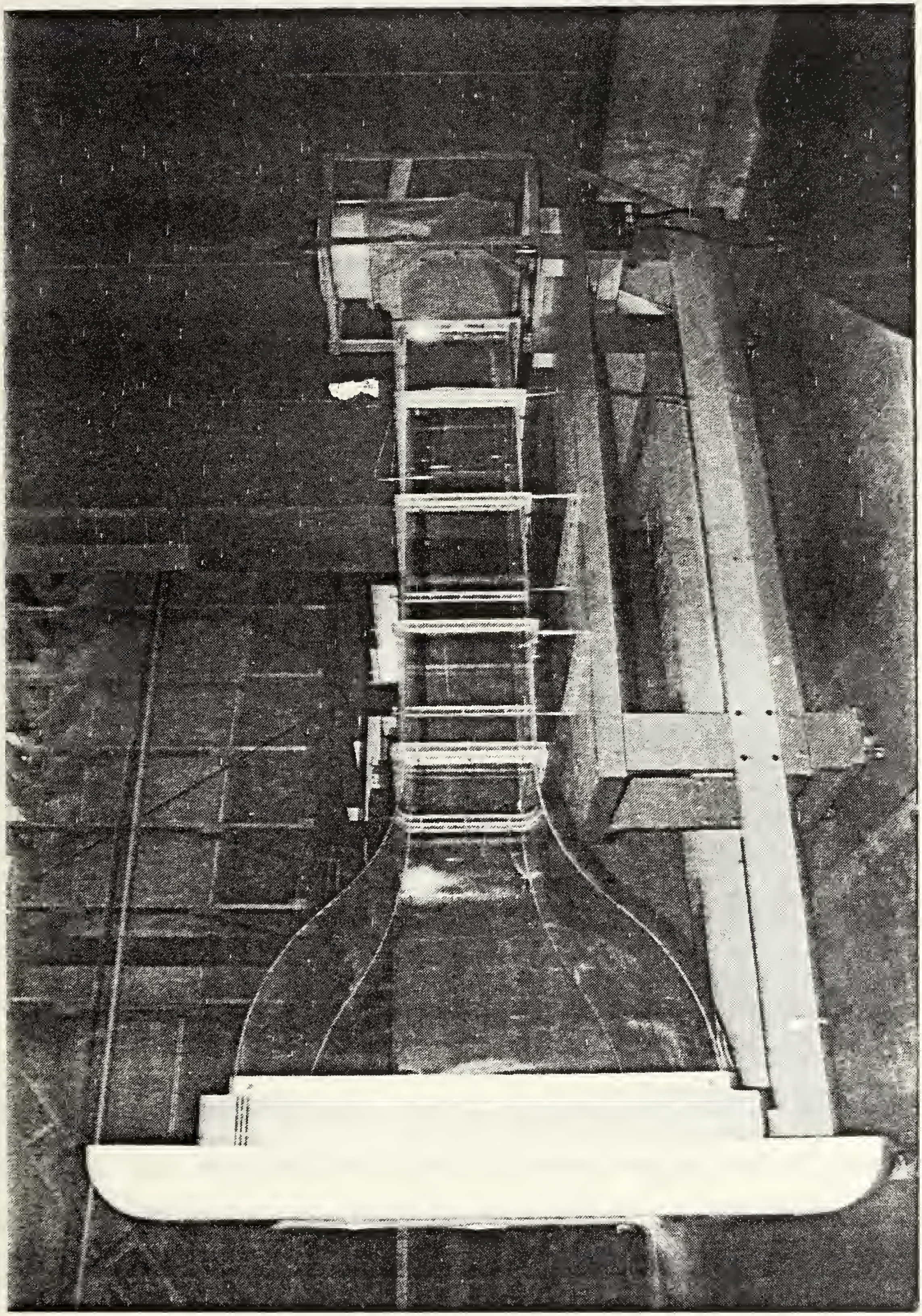

Figure 2. The Completed Tunnel

connection to the salvaged fan and motor assembly. Design of this section is such that total area is constant from end to end, ensuring no additional contraction of the flow.

The salvaged fan and motor assembly includes a fixed pitch four bladed fan and a 90 degree turn (with turning vanes) to exhaust the air vertically into the atmosphere. The fan is driven by a one horsepower, adjustable speed, d.c. electric motor manufactured by Minarik Electrical Company. Tunnel velocity is controlled by adjusting the speed of the motor. The controller for the motor is mounted to the table, directly below the motor.

B. CHARACTERISTICS OF TEST SECTION FLOW

The current tunnel's air flow measurements were performed by Bolinger [Ref. 6:pp. 18-21]. These tests revealed that at a reference velocity of approximately 9.1 feet per second in the center of the tunnel, the velocity profile was almost uniform and the turbulence intensity was about 1%. For good quality flow visualization, it is desirable that the velocity profile be very uniform and that turbulence should be well below this 1% value.

C. VISUALIZATION EQUIPMENT

Because the renovated full scale tunnel's future location is two miles from the main campus, the one quarter scale tunnel required its own separate visual-mechanics generating devices. To match the large tunnel's capabilities (for flow quality checks) and to ensure a variety of methods for demonstration and small scale research, three techniques were developed.

1. Smoke Wire

A smoke wire system, as depicted in Figure 3, was constructed using a dc power supply. This system was selected over ac for ease of control and because the steady current results in smoother and better-defined smokelines. Because of the relatively short duration of smoke generation for a single wire coating, it is important that the flow event being photographed, the lighting, the camera, and the smoke be properly controlled and synchronized. To accomplish this, a timing circuit was built using the design presented by Goldstein [Ref. 4:p. 333] (with slight modifications) and illustrated in Figure 4.

The power set potentiometer controls the amount of current passing through the wire, and the pulse-length potentiometer controls the length of time this current is applied. The burst potentiometer can be switched into the circuit to enable the operator to control the frequency of current pulses during the burn, resulting in an intermittent pattern of smoke. The wire is heated and cooled because of the pulsed voltage; the smoke density varies in a similar manner, and streak-time lines can be formed. An additional potentiometer in this "switched" circuit controls the on-off

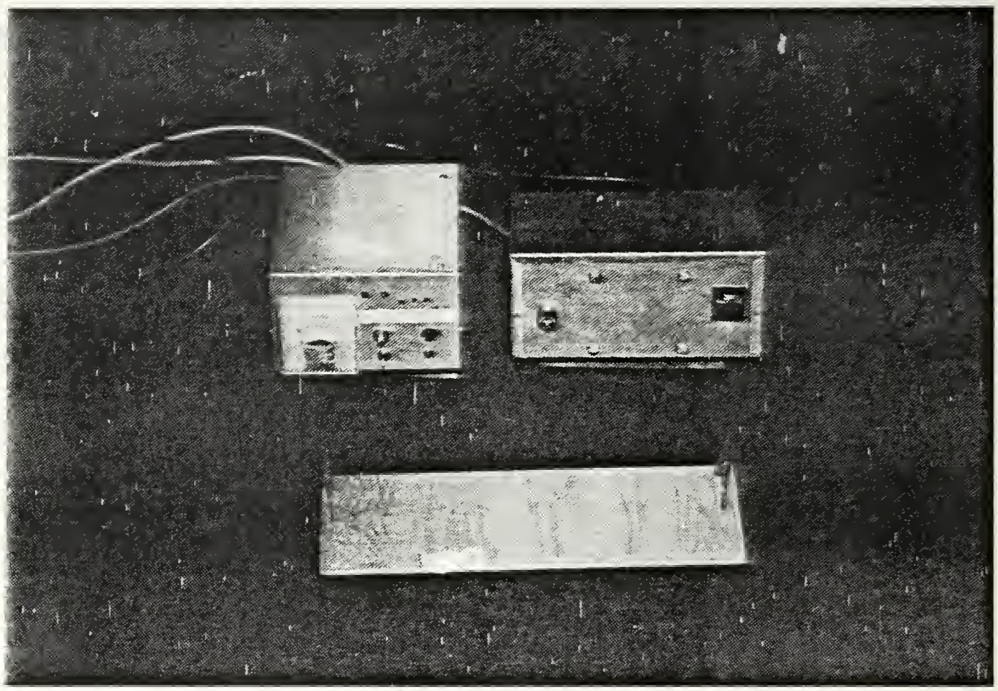

Figure 3. The Smoke Wire System

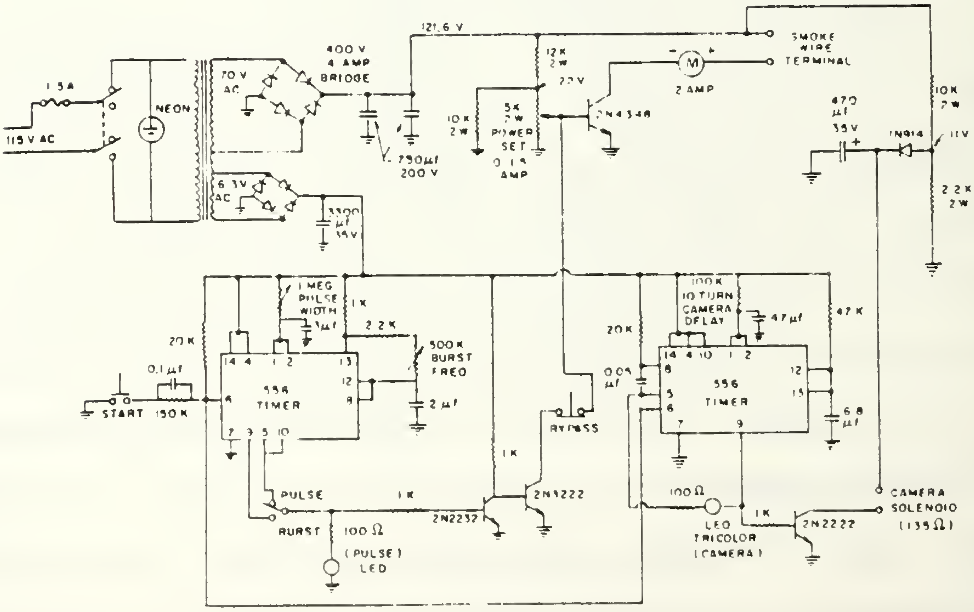

Figure 4. The Circuit Design for the Smoke Wire System

period of these bursts. The corner delay potentiometer controls the time delay before the camera is triggered.

All these controls can be preset, reducing the photographing of a given event to a single-step operation. The circuit applies power to the smokewire, and, with the appropriate user-set delay, it activates the camera and lights using a solenoid attached to the camera trigger. After the controls are set, the wire is oiled using a cloth applicator, and the start button is depressed. This causes the smoke to be generated and the camera to be triggered when the smoke has reached the desired intensity and location. The timing circuit is invaluable in the practical application of the smokewire.

2. Aerosol Injection

Weighing cost against complexity of construction, a commercial theatrical fog and smoke machine was purchased. This device, a Rosco model 8211 series 3 machine, is a thermal fog generator designed for high velocity fog output, see Figure 5. The machine is part of a system [Ref. 8], the other component being Rosco Fog Fluid. This unique fluid formulation will not flame, will not cause throat or eye irritation and will leave no oily residue because it contains no petroleum distillate. The operating temperature, air pressure, output nozzle and limiting orifice of the machine have been specifically set to maximize vaporization of the fluid.

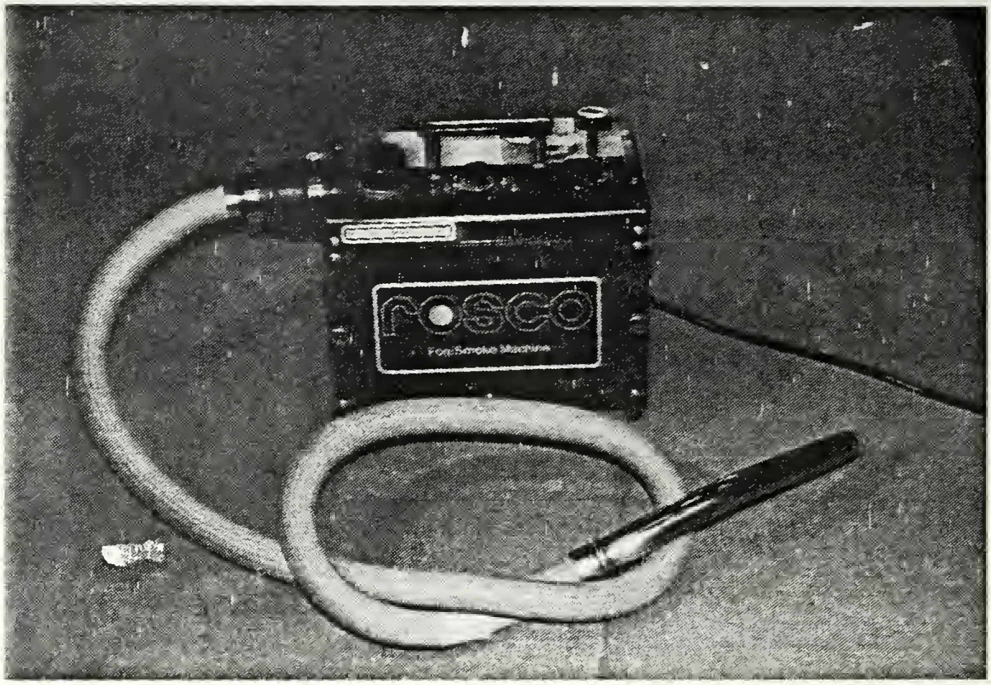

Figure 5. The Aerosol Injection System

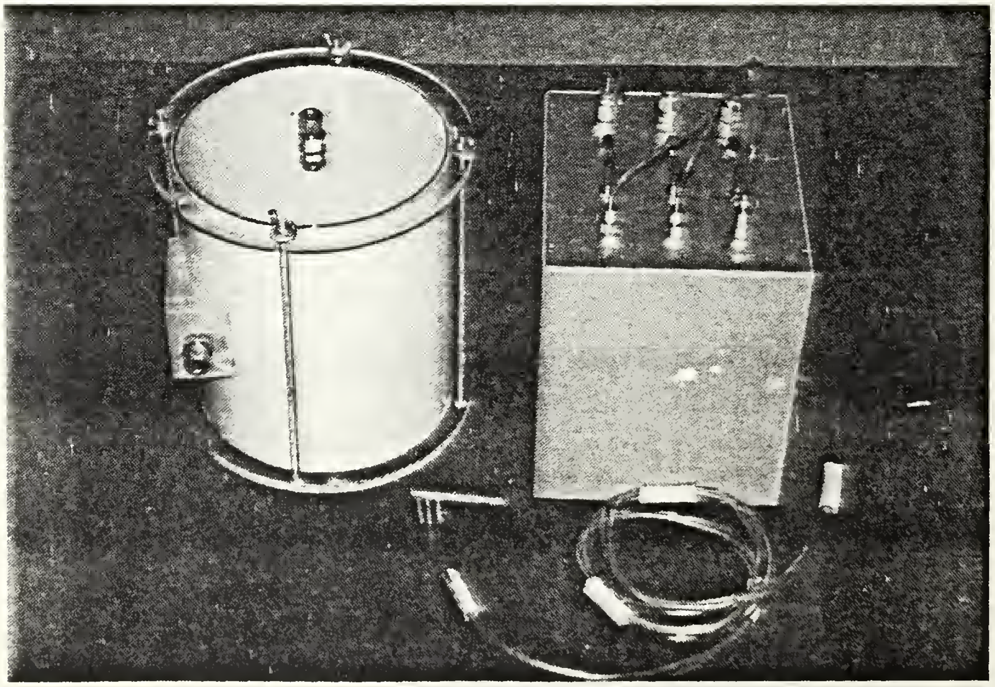

Figure 6. The Helium Bubble System

To operate the system, fluid is placed in the reservoir which is in turn pressurized to about 30 lbs. per square inch. Fluid is drawn from the tank and forced at high pressure into the heat exchanger where it is heated to a temperature above its vaporization. When the heat exchanger has reached its operating temperature, the operator applies power to the solenoid valve, allowing fluid into the heat exchanger. The heated and pressurized liquid is then discharged through the nozzle orifice where it vaporizes and, upon mixing with cooler air, condenses into millions of fine particles of .5 to 25 microns (controllable with output). This fog then passes through a one inch inside diameter plastic pipe for injection into the desired test locations, depending on specific research needs.

3. Helium Bubbles

A helium bubble system was constructed based on the system described by Hale [Ref. 9] and currently in use in the full scale tunnel. It consists of a bubble generator console, a low speed bubble ejector head, and a neutral density bubble centrifuge, as shown in Figure 6. The head consists of three concentric tubes. Helium traveling through the inner tube is inserted into the bubble film solution (BFS) passing through the annular passage. The bubbles are blown off the tip of the head by a continuous blast of air through the shroud passage. The bubble size, density, and rate of generation are controlled by adjusting the helium and bubble solution micrometering valves at the console. Small bubbles of about 1/8-inch diameter are generated in the head at a rate of up to 500 bubbles per second.

Neutrally buoyant bubbles are usually generated at near maximum helium flow rates. However, it is extremely difficult to maintain this precise mixture of helium and bubble solution. Since it is critical to use neutrally buoyant bubbles in order to correctly trace the flow, a neutral density bubble centrifuge was constructed and used in series between the console and ejector head.

The centrifuge allows for a much larger range of mixtures of the helium and bubble solution and sorts out the light and heavy bubbles, thus insuring that only neutrally buoyant bubbles are allowed to leave the unit. After leaving the centrifuge, the neutrally buoyant bubbles pass through a 1/2 inch inner diameter plastic pipe to be entered in the flow at differing locations as research requires. Because of the small size and low reflectivity of the bubbles, careful selection of light sources and extreme care in their placement is required.

IV. FLOWS AROUND BODIES

Flows around various shapes, including both streamlined and unstreamlined bluff bodies, have been studied for years using differing flow visualization techniques. Because these studies have been carried on by so many researchers, bluff body flow phenomena can be used as a baseline check for new flow visualization facilities.

Flows past unstreamlined structures often produce oscillating instabilities. Mueller [Ref. 2:p. 340] notes that these instabilities lead to an organized and periodic shedding of vortices in the wake as the flow separates alternately from the body. The flow field exhibits a dominant frequency and thus, the drag and pressure forces acting on the body are also unsteady. For uniform flows past stationary structures, universal similarity exists in the wake of such structures. Examples of unstreamlined bluff bodies include those with rectangular cross section, cylinders (with axis perpendicular to the flow) and spheres.

The most common example of a streamlined body is an airfoil. Many studies have been performed concerning the laminar flow around differing shaped airfoils and the resulting transition from laminar to turbulent flow as the angle of attack is increased. This transition may be described as a series of events that take place more or less continuously, depending on the flow problem. Since turbulence is essentially a three-dimensional phenomenon, the breakdown of a two-dimensional laminar flow may be viewed as the process whereby finite-amplitude velocity fluctuations, or traveling wave disturbances, acquire significant three-dimensionality. More graphically, turbulence is that process where parallel two-dimensional vortex flow lines become a totally disorganized three-dimensional intertwined jumble. [Ref. 2:p. 337]

To ensure that the techniques developed in this investigation are capable of being used for the purposes listed in Chapter II, flows around three shapes of bodies were investigated. A 3 1/2 inch aluminum cube was used for the photographs of flow around a block of rectangular cross section. A vertically mounted, 1 1/2 inch diameter, 15 inch long aluminum rod was used for the photographs of flow around a cylinder. And, for the photographs of flow around an airfoil, a 15 inch long NACA 63-215 airfoil with 3 1/2 inch chord was constructed of wood.

All three bodies were bolted through the floor of the test section, directly in the middle both laterally and longitudinally. Both the cylinder and airfoil were long enough to stretch from the floor to the ceiling of the tunnel.

V. FINAL SET UP AND RESULTS

A. VELOCITY AND TURBULENCE MEASUREMENTS

A permanent pitot static probe was installed in the ceiling (and door) of the tunnel, four inches upstream of the end of the constant area part of the test section and centered laterally. The tube protruded 3 1/4 inches into the flow to ensure avoidance of boundary layer interference.

For calibration, velocity was measured against both actual RPM of the motor and percent RPM of the controller. The results of these measurements are shown in Table 1.

The percent RPM of the controller is a direct gage readout. However, to measure the actual RPM of the motor a digital optical tachometer was used. This instrument operates by directing a collimated light beam onto a reflective marker attached to the rotating motor shaft. The reflected pulses are compared against an internal time base and resultant RPM is read directly from an LED readout.

The total pressure and static pressure lines from the pitot static probe were attached to an Airflow Developments Ltd., Model EDM 2500 E, micromanometer. Velocity could then be indirectly measured by using the pressure difference reading on the manometer gage (in hundredths of inches of water) and converting through the formula

$$V = \left(\frac{2\rho_w g \Delta h}{\rho_a \, 12}\right)^{1/2} = 2.9(T\Delta h)^{1/2}$$

TABLE 1

TUNNEL VELOCITY CALIBRATION
(T = 520 deg R)

% RPM	RPM	Δh INCHES WATER	VEL (fps)
5	66	_____	_____
10	160	_____	_____
15	245	.0025	3.31
20	335	.0030	3.62
25	437	.0070	5.53
30	521	.0100	6.61
35	619	.0115	7.09
40	709	.0160	8.36
45	809	.0200	9.35
50	892	.0250	10.46
55	980	.0300	11.45
60	1072	.0350	12.37
65	1168	.0415	13.47
70	1265	.0500	14.79
75	1358	.0580	15.93
80	1452	.0650	16.86
85	1549	.0750	18.11
90	1642	.0850	19.28
95	1737	.0950	20.38
100	1805	.1150	22.43

A good tunnel must have very uniform flow across the test section. The uniformity was checked using a seven tube pitot static rake which was constructed to hasten the measurements; see Figure 7. The rake was mounted vertically with the individual tubes 2 inches apart. After a set of measurements was taken, the rake was moved 2 inches laterally from the previous position where another set of measurements was taken. This procedure enabled mapping every two inches both vertically and horizontally across the test section. These measurements were in hundredths of inches of water as read through the same micromanometer used in the velocity calibration. The conversion to velocity was also the same as that used in the velocity calibration.

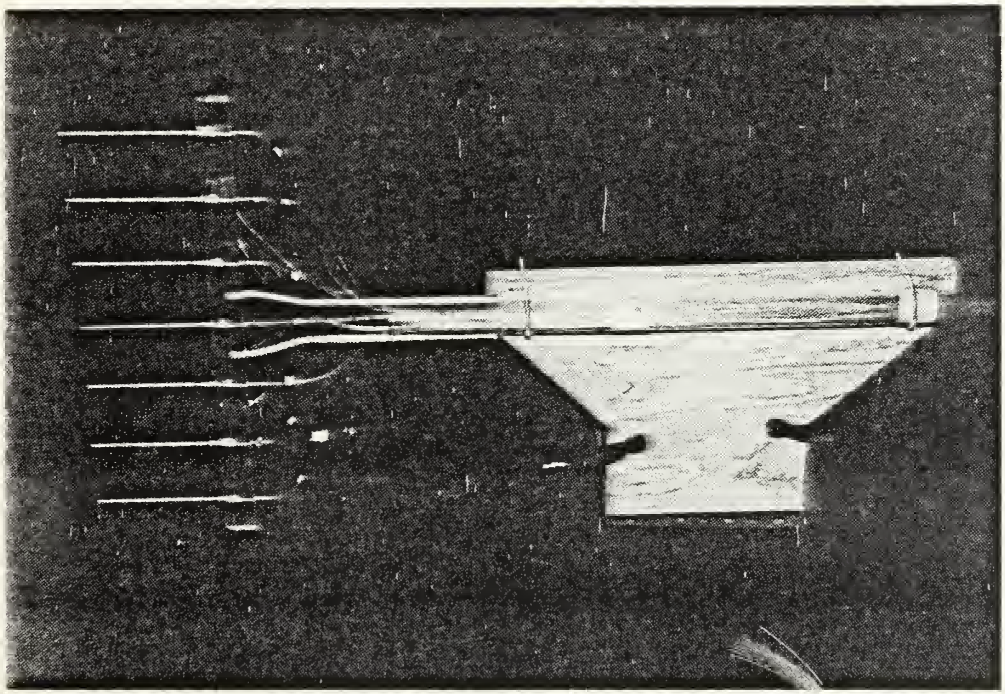

Figure 7. The Pitot Static Rake

To map the entire 15 x 24 inch cross section 84 individual readings and 12 rake locations were required, with results listed in Table 2. With calibration velocity set at 9.35 fps, the mean velocity equaled 9.21 fps, a difference of 1%. Before each set of rake readings was taken, the micromanometer was reattached to the permanent pitot static probe to ensure calibration of the tunnel to .02 inches of pressure (9.35 fps).

Turbulence intensity was measured using a hot wire anemometer, located in the center of the flow field at the downstream end of the test section. Turbulence intensity varied from .7 to 1.05% over the velocity range of the tunnel.

B. SMOKE WIRE

The smoke wire was mounted horizontally, 5 1/4 inches above the floor and 1 inch downstream from the front of the test section when using both the cylinder and airfoil. Because the block of rectangular cross section was only 3 1/2 inches high, the wire was located 2 inches horizontally from the floor when studying that shape.

After coating the wire with vegetable oil, manual activation of the wire resulted in a smooth sheet of smoke which lasted for approximately 3 seconds. Manual operation allowed control of the current flow timing in response to differing amounts of oil on the wire. The auto mode resulted in oil being left on the wire or current flow after

TABLE 2

VELOCITY MAP (FPS)

height (inches)	inches across tunnel (L to R with flow)											
	1	3	5	7	9	11	13	15	17	19	21	23
13.5	9.12	8.99	9.35	9.12	9.12	9.23	9.23	9.35	8.99	8.87	9.12	9.12
11.5	8.99	9.12	9.12	9.23	9.35	9.35	9.35	9.35	9.58	9.35	8.99	8.75
9.5	8.99	9.35	9.23	9.35	9.47	9.35	9.35	9.58	9.35	9.35	9.23	8.87
7.5	9.12	9.12	9.35	9.35	9.47	9.47	9.58	9.35	9.47	9.47	9.23	9.23
5.5	8.87	9.12	9.12	9.35	9.35	9.58	9.23	9.35	9.23	9.23	9.23	8.99
3.5	8.87	8.99	9.12	9.23	9.35	9.35	9.35	9.35	9.23	9.12	9.35	8.99
1.5	8.99	9.35	9.12	9.23	9.35	9.12	8.99	8.99	8.87	8.75	8.62	9.23

tunnel velocity set at 9.35 fps (T=60 deg F)

mean velocity = 9.21 fps

the oil had burned off. To keep the sheet neatly intact a tunnel velocity of 3.3 feet per second was used.

All test runs were conducted at night because reflections from skylights in the lab facility prevented unimpeded daylight photography. To illuminate the smoke sheet, three spot-lights were used. One was positioned over the test section for general illumination and two others were place on either side of the tunnel to illuminate the smoke sheet. To eliminate reflections and provide a contrasting background to the smoke, flock paper was applied to the floor of the test section.

A Nikon model N2000, 35 mm camera was used for all photographic recording. Best results came from positioning the camera approximately 2 feet above the smoke and shooting down at a small angle from vertical, over the body being studied. Kodak TMAX ASA-400 film was used with a shutter speed of 1/250 second and an aperture setting of f-1.4. The resulting photographs are shown in Figures 8-13.

C. HELIUM BUBBLE

The helium bubble nozzle was inserted through the floor of the tunnel, 1 inch downstream from the front of the test section and laterally in the middle. The nozzle rose above the floor 5 inches when using either the cylinder or airfoil and 2 inches with the cube. Fine adjustment of the control box resulted in bubbles of approximately 1/16 to 1/8 inch diameter being introduced into the flow. A velocity of 9.35

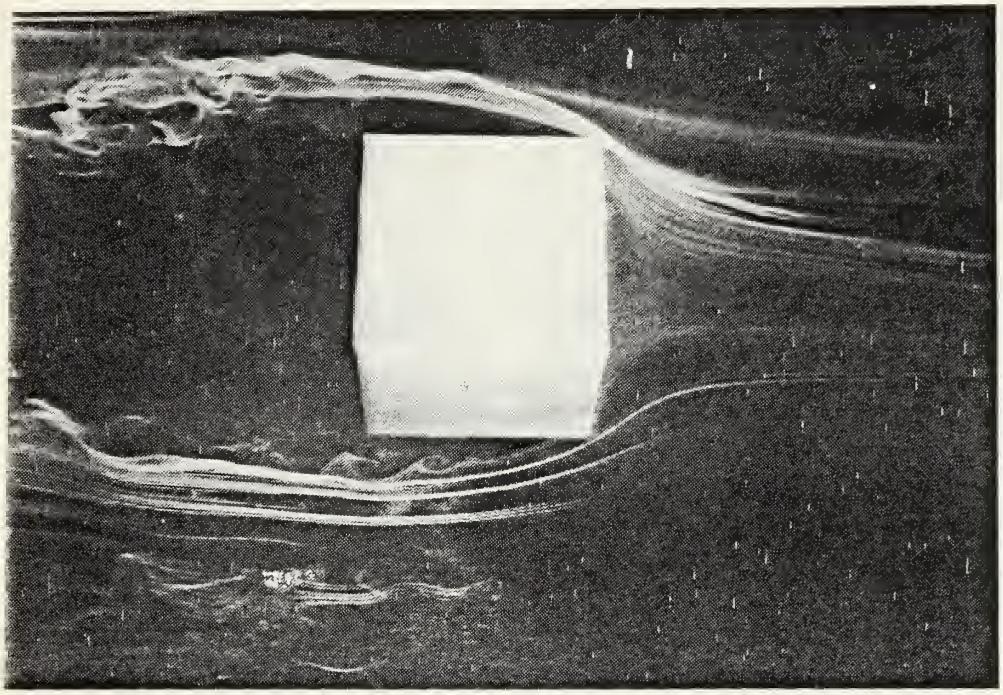

Figure 8. Smoke Wire Systems. Flow Around Block

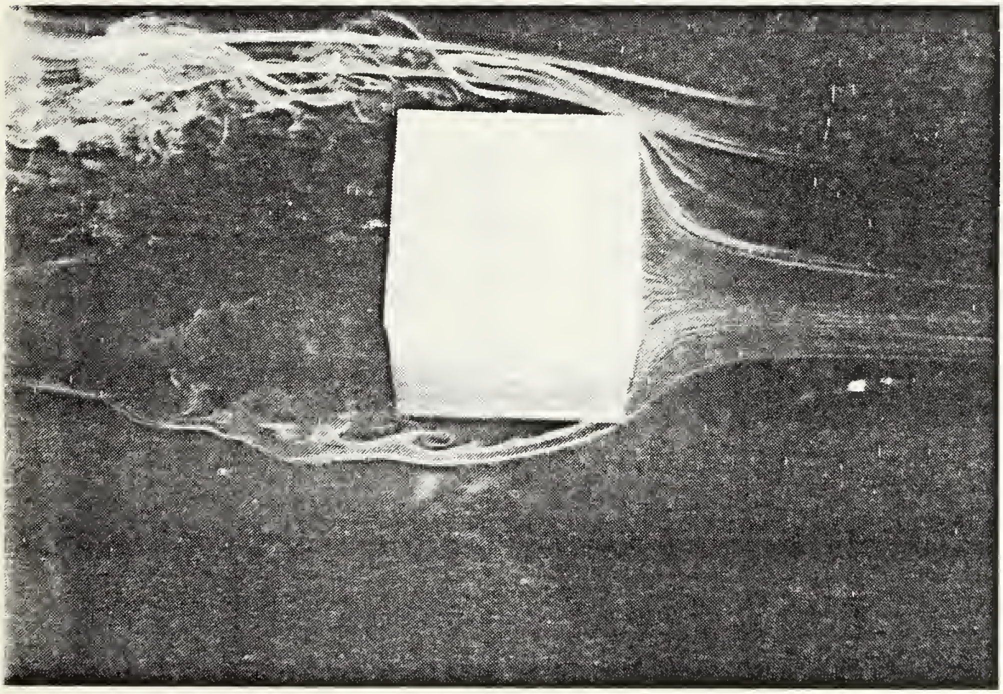

Figure 9. Smoke Wire System. Flow Around Block

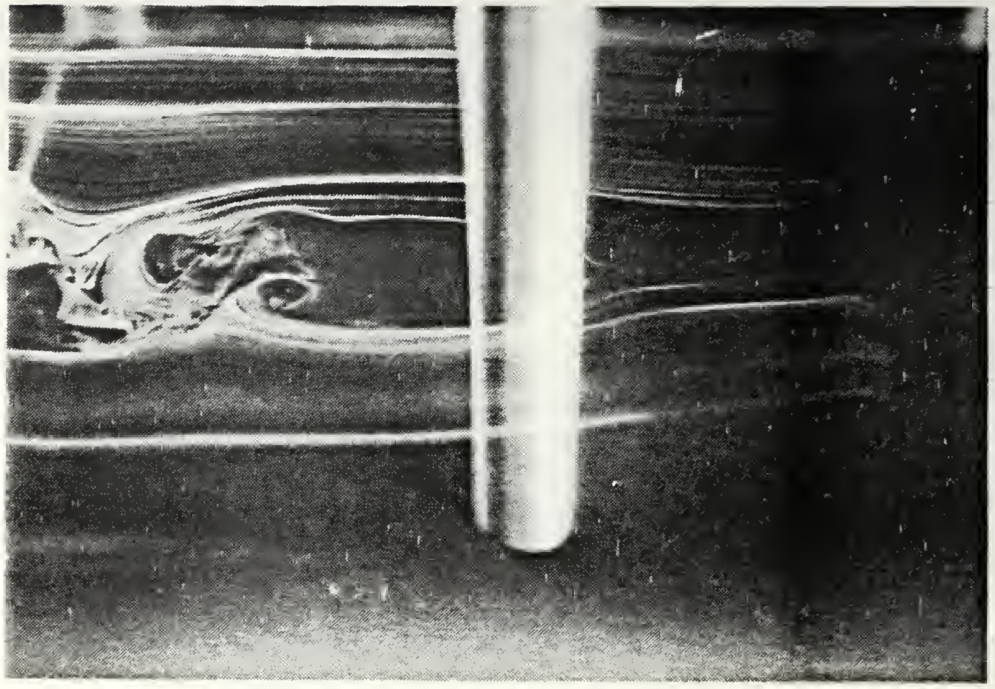

Figure 10. Smoke Wire System. Flow Around Cylinder

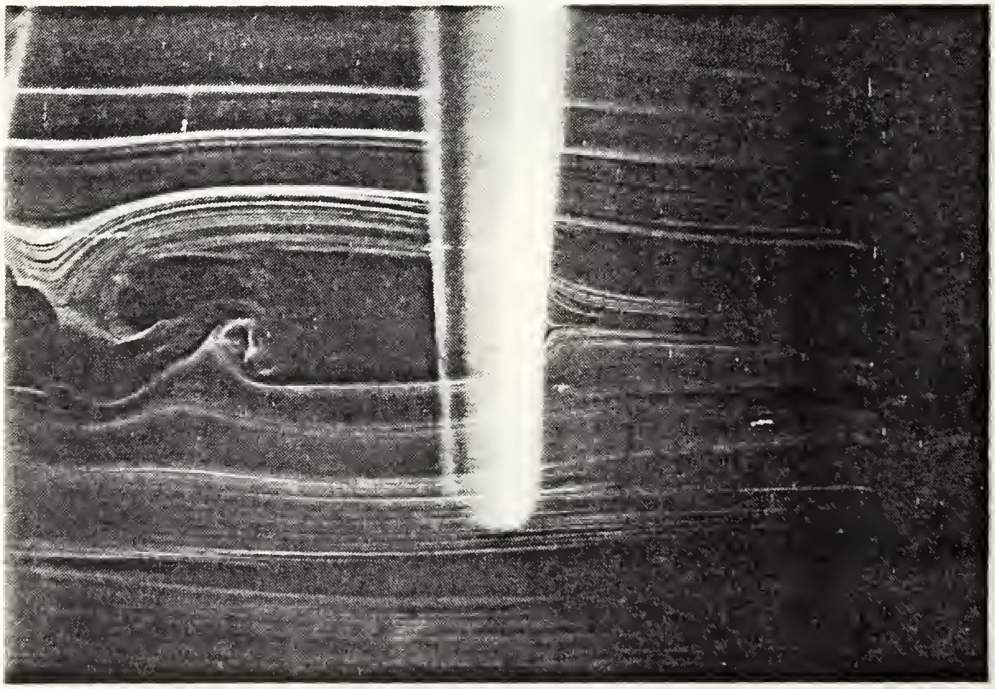

Figure 11. Smoke Wire System. Flow Around Cylinder

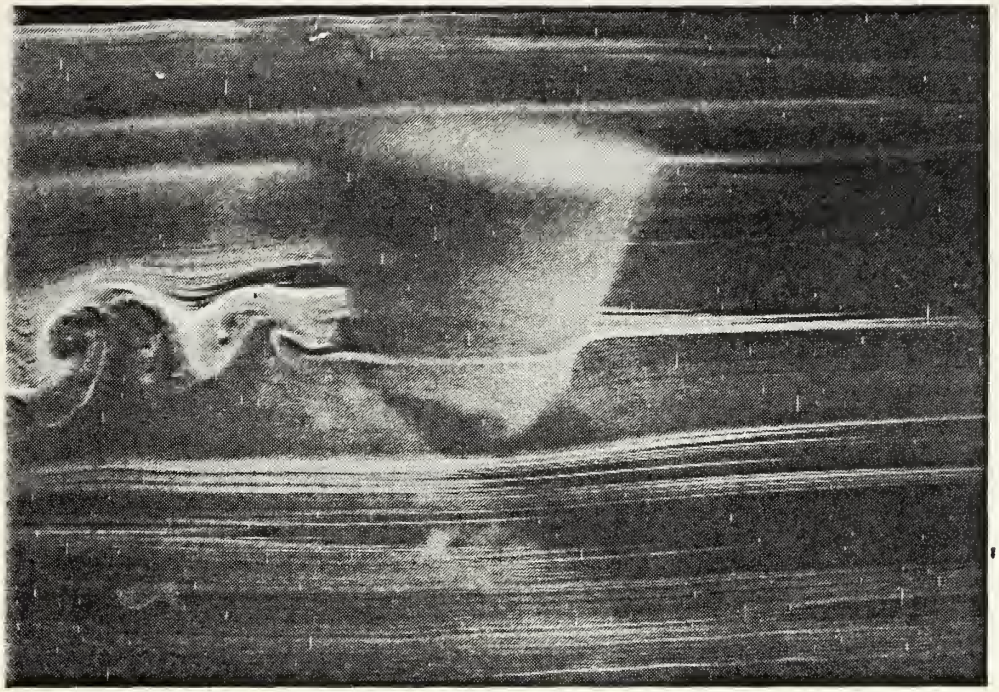

Figure 12. Smoke Wire System. Flow Around Airfoil

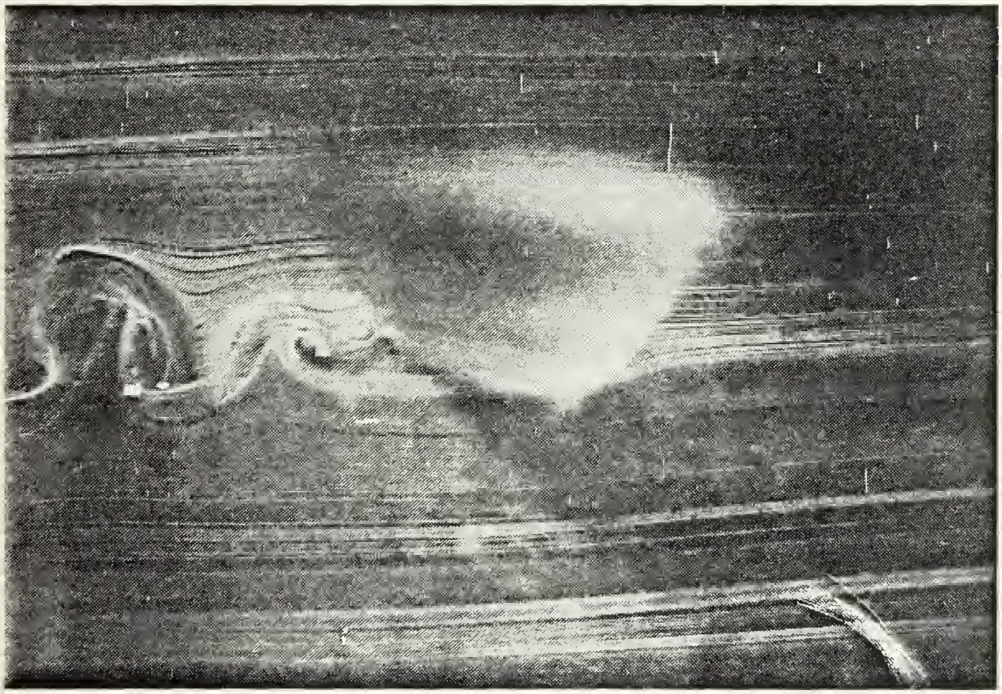

Figure 13. Smoke Wire System. Flow Around Airfoil

feet per second was used with this technique to give smooth bubble flow and to match the velocity used with helium bubbles in the full scale tunnel.

Again all runs were conducted at night to prevent the reflection problems caused by the skylights. However, when photographing the helium bubbles, correct placement of lighting was much more critical. No general lighting was used because it caused the light from the bubbles to blend in with the ambient light.

Initially, the bubbles were lit with directed spot lights, and, even though the bubbles were visible to the naked eye, the camera was unable to contrast them from the two aluminum shapes or even the flock paper for acceptable photographs. Finally, best results came from an arc lamp beam directed through the intake screens onto the helium bubble stream, combined with a small lamp to illuminate the bubbles as they moved downstream past the different bodies. Also, both the aluminum block and cylinder were painted flat black, and black cloth was draped over the portion of the test section not being used to further eliminate any stray light.

The Nikon model N2000 camera was used with placement in relation to the tunnel and bodies similar to that used with the smoke wire. However, for this method of flow visualization, photographs of the streaklines that the bubbles make as they flow around the various shapes is the desired result. Therefore, the shutter speed needs to be slow enough to allow the bubbles to traverse a great enough distance. To accomplish this the shutter speed was set to 1/4 second which allowed the bubbles in the free stream to travel approximately 28 inches. After the shutter speed was set, different aperture settings were tried with best results coming from a setting of f-1.4. Again, TMAX ASA-400 film was used. The resulting photographs are shown in Figures 14-19.

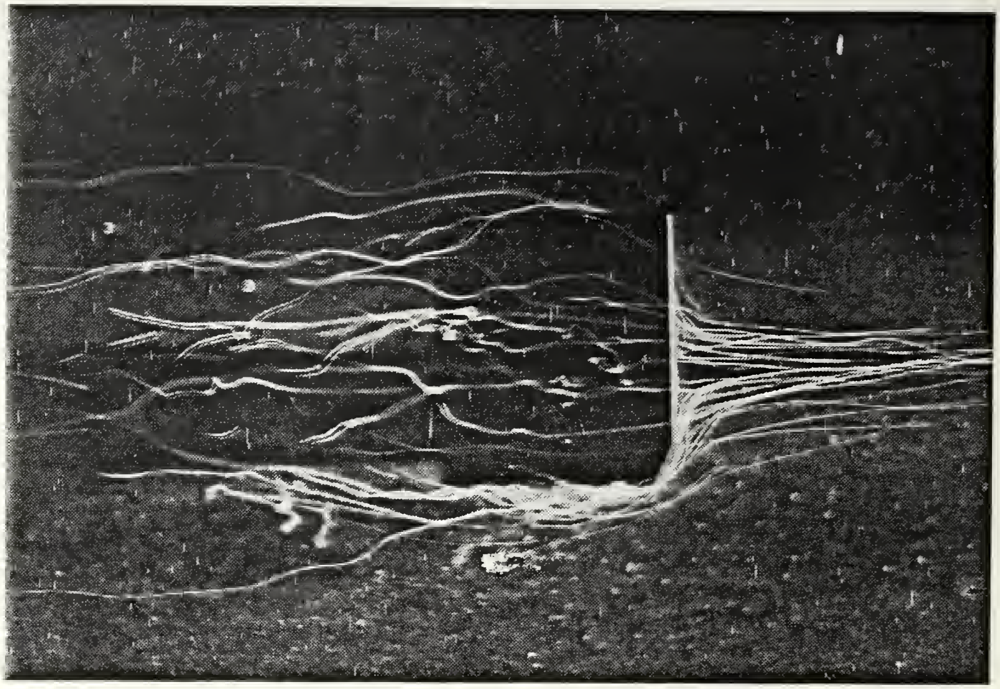

Figure 14. Helium Bubble System. Flow Around Block

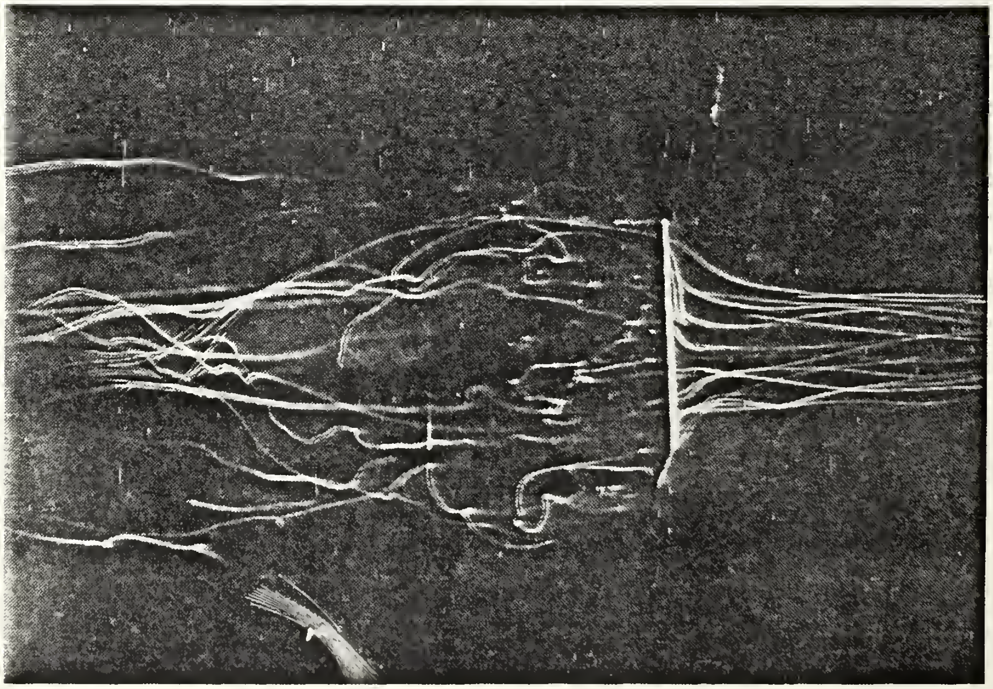

Figure 15. Helium Bubble System. Flow Around Block

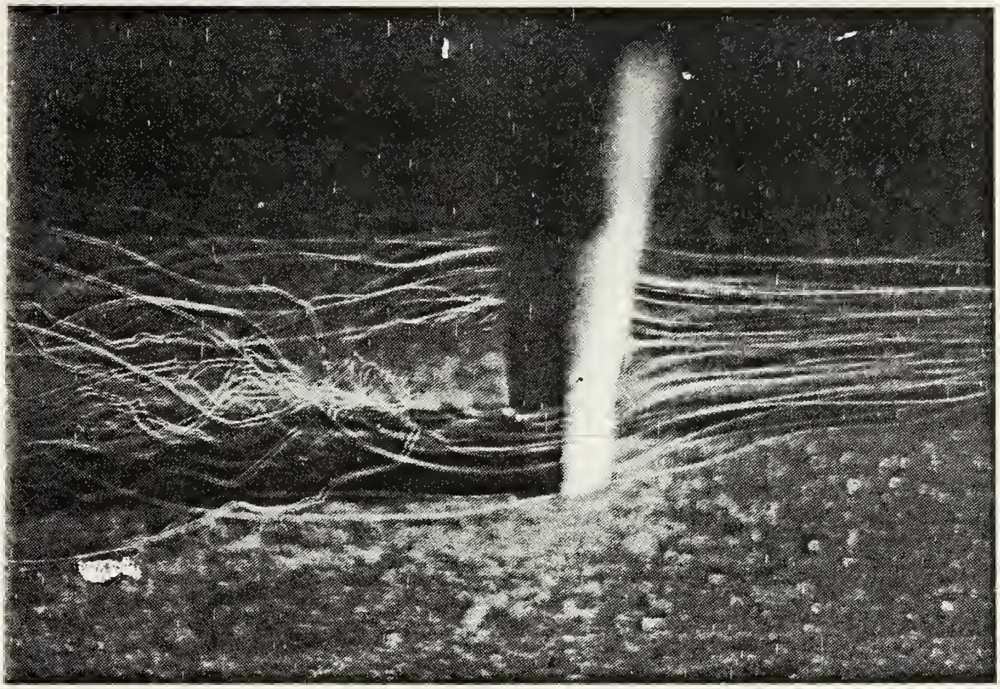

Figure 16. Helium Bubble System. Flow Around Cylinder

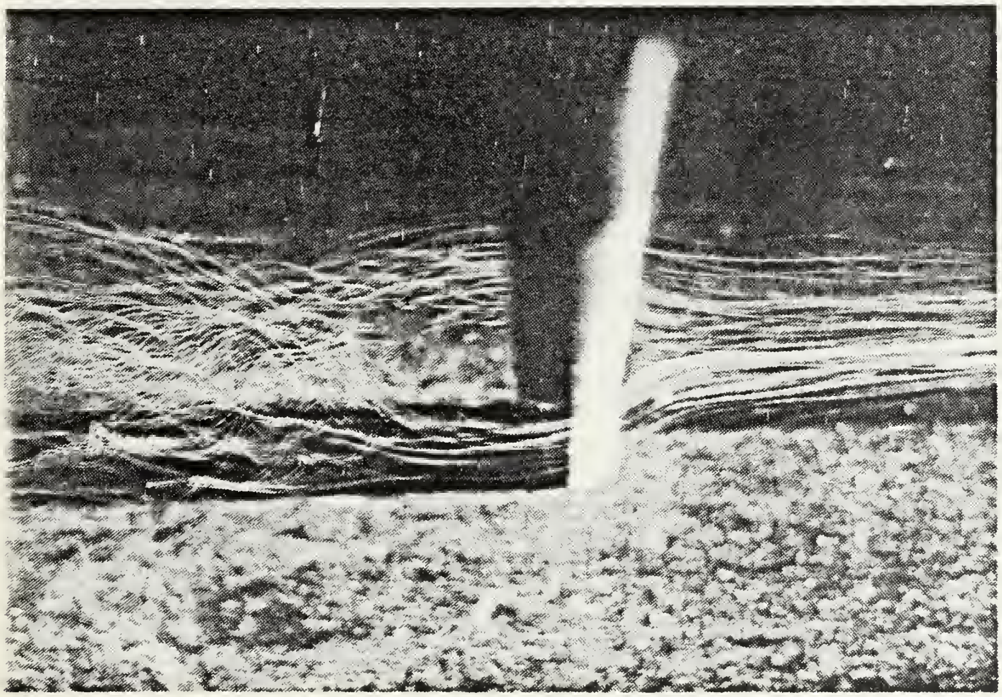

Figure 17. Helium Bubble System. Flow Around Cylinder

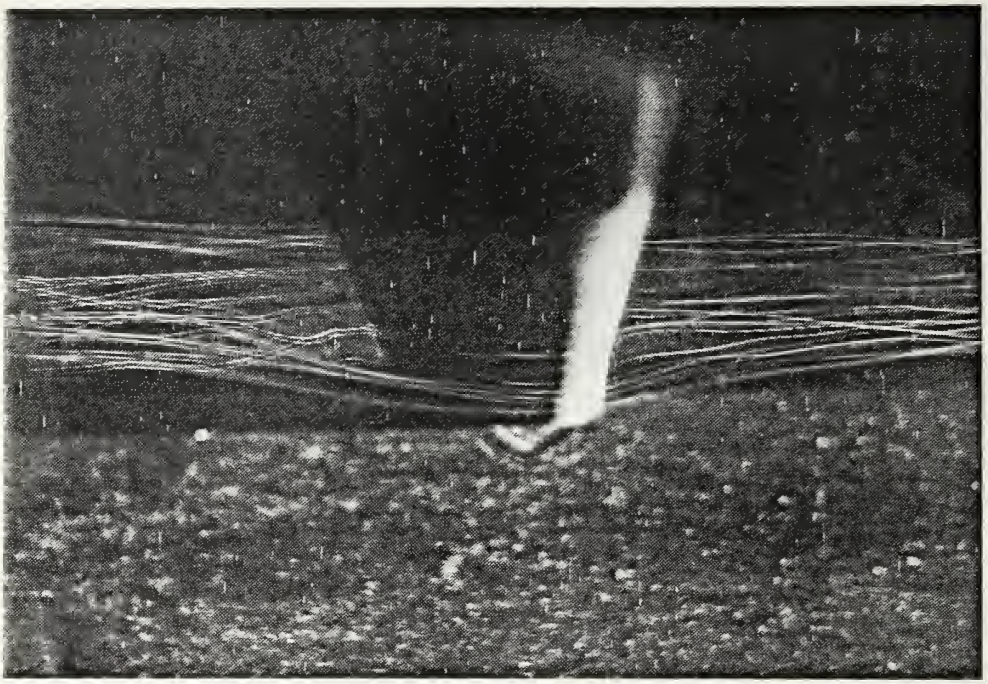

Figure 18. Helium Bubble System. Flow Around Airfoil

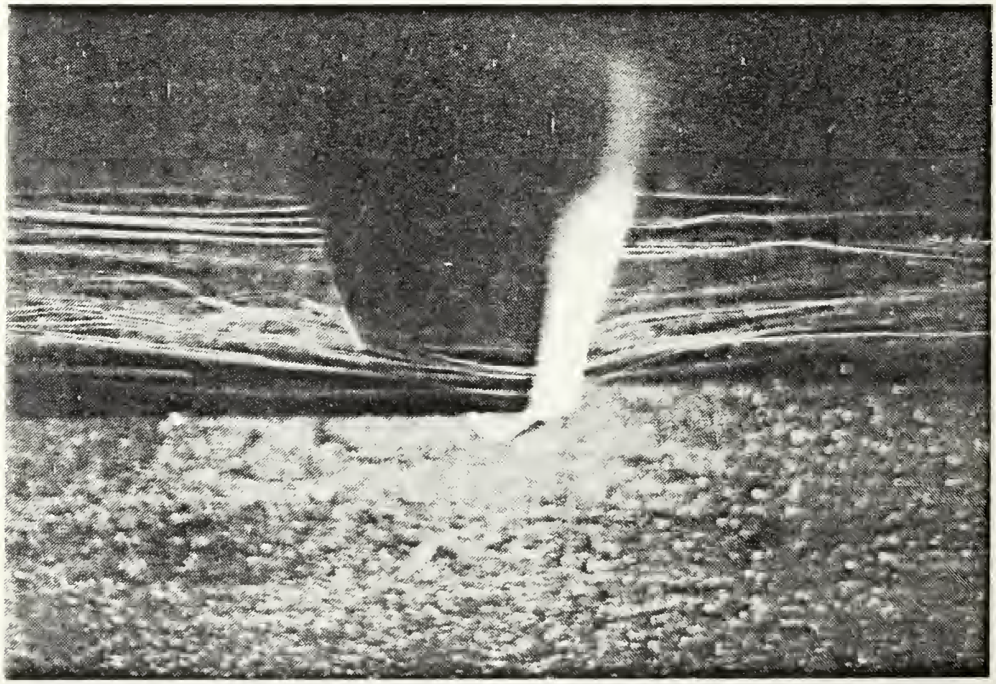

Figure 19. Helium Bubble System. Flow Around Airfoil

VI. CONCLUSIONS AND RECOMMENDATIONS

A. APPLICABILITY OF RESULTS TO REQUIREMENTS

Construction to one quarter scale will allow quality-of-flow testing for the planned renovated tunnel. Initial velocity mapping reveals that the velocity profile is almost uniform across the test section, with mean velocity differing from calibrated velocity by only 1%. Additionally, overall tunnel turbulence intensity was below 1%.

The relatively small overall size allows placement of the tunnel in the lab facility where there is easy access to viewing and use. The ability of the tunnel to provide satisfactory flow visualization was demonstrated using two techniques. Additionally, the tunnel demonstrated a rather large velocity range. This capability combined with the relatively small size should facilitate further development for small scale research and flow visualization demonstrations which were the two other objectives of this study.

B. IMPROVEMENTS AND FUTURE WORK

Because the scale on the micromanometer was too large, the velocity measurements of both the permanent pitot static probe and rake were subject to human errors in reading the gage. More accurate readings could be made using an instrument with smaller scale or a hot-wire set up capable of direct digital readings. In this same vein, future work should include complete mapping of the test section from front to back, including the small contraction section.

Secondly, the entire tunnel is subject to very small vibrations resulting from the fan and motor assembly not being perfectly balanced. At certain velocities, such as 62% RPM, the vibrations become resonant and shake the intake section to a small but unsatisfactory level. To eliminate this problem, future installation of a motor shaft bearing which is secured separately from the fan housing should be accomplished.

Finally, the quarter scale tunnel is currently located in front of the intake of the larger tunnel so that the exhaust may be sucked out of the building using the larger tunnel's exhaust port. This requires operation of both tunnels even though only the smaller one is in use and precludes the use of the larger tunnel whenever the smaller one is operating. Construction of a separate exhaust port is required for efficient and economical use of the lab facility.

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